Prototype development of a Geostationary Synthetic Thinned Aperture Radiometer, GeoSTAR

A. B. Tanner, W. J. Wilson, P. P. Kangaslahti, B. H. Lambrigsten, S.J. Dinardo
Jet Propulsion Laboratory
Pasadena, CA

J.R.Piepmeier
Goddard Space Flight Center
Greenbelt, MD

C.S. Ruf, S.Rogacki, S.M. Gross, S. Musko
University of Michigan
Ann Arbor, MI

Abstract—**Preliminary details of a 2-D synthetic aperture radiometer prototype operating from 50 to 58 GHz will be presented. The instrument is being developed as a laboratory testbed, and the goal of this work is to demonstrate the technologies needed to do atmospheric soundings with high spatial resolution from Geostationary orbit. The concept is to deploy a large sparse aperture Y-array from a geostationary satellite, and to use aperture synthesis to obtain images of the earth without the need for a large mechanically scanned antenna. The laboratory prototype consists of a Y-array of 24 horn antennas, MMIC receivers, and a digital cross-correlation sub-system. System studies are discussed, including an error budget which has been derived from numerical simulations. The error budget defines key requirements, such as null offsets, phase calibration, and antenna pattern knowledge. Details of the instrument design are discussed in the context of these requirements.**

1. INTRODUCTION

The National Oceanic and Atmospheric Administration (NOAA) has for many years operated Polar-orbiting Operational Environmental Satellite systems (POES) in low-earth orbit (LEO), and Geostationary Operational Environmental Satellite systems (GOES) in geostationary earth orbit (GEO). The POES satellites have been equipped with both infrared (IR) and microwave (MW) atmospheric sounders, which together make it possible to determine the vertical distribution of temperature and humidity in the troposphere- even under cloudy conditions. In contrast, the GOES satellites have only been equipped with IR sounders. Geostationary MW sounders have not yet been feasible due to the large apertures required to achieve sufficient spatial resolution. As a result, and since clouds are almost completely opaque at infrared wavelengths, GOES soundings can only be obtained in cloud free areas and in the less important upper atmosphere, above the cloud tops. This has hindered the effective use of GOES data in numerical weather prediction. Full sounding capabilities with the GOES system is highly desirable because of the advantageous spatial and temporal coverage that is possible from GEO. While POES satellites provide coverage in relatively narrow swaths, and with a revisit time of 12-24 hours or more, GOES satellites can provide continuous hemispheric or regional coverage, making it possible to monitor highly dynamic phenomena such as hurricanes.

In response to a 2002 NASA Research Announcement calling for proposals to develop technology to enable new observational capabilities from geostationary orbits, the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR) was proposed as a solution to the GOES MW sounder problem. GeoSTAR synthesizes a large aperture to measure the atmospheric parameters at microwave frequencies with high spatial resolution from GEO without requiring the very large and massive dish antenna of a real-aperture system. With sponsorship by the NASA Instrument Incubator Program (IIP), an effort is currently under way at the Jet Propulsion Laboratory to develop the required technology and demonstrate the feasibility of the synthetic aperture approach – in the form of a small ground based prototype. This is being done jointly with collaborators at the NASA Goddard Space Flight Center and the University of Michigan. The objectives are to reduce technology risk for future space implementations as well as to demonstrate the measurement concept, test performance, evaluate the calibration approach, and assess measurement accuracy. When this risk reduction effort is completed, a space based GeoSTAR program can be initiated, which will for the first time provide MW temperature and water vapor soundings as well as rain mapping from GEO, with the same measurement accuracy and spatial resolution as is now available from LEO – i.e. 50 km or better for temperature and 25 km or better for water vapor and rain.

2. Instrument Concept

As illustrated in Figure 1, GeoSTAR consists of a Y-array of horn antennas and receivers, and a digital system which computes cross-correlations between the IF signals of the receivers. All of the horn antennas are pointed in the same direction, and complex cross-correlations are formed between all possible pairs of antennas of the array. In the small scale example of Figure 1 there are 24 antennas and 276 correlations (=24*23/2). Each correlator and antenna pair forms an interferometer which measures a particular spatial harmonic of the brightness temperature image across the field of view (FOV). The spatial harmonic depends on the spacing between the antennas and the radio wavelength. As a function of antenna spacing, the complex cross-correlation measured by an interferometer is called the visibility function. This function is the Fourier transform of the function of brightness temperature versus incidence angle. By sampling the visibility over a range of spacings one can reconstruct, or "synthesize," an image in a computer by discrete Fourier transform. These techniques are well known in radio astronomy, but are relatively new to earth imaging problems.

The "Y" configuration of the GeoSTAR array is motivated by the need to measure a complete set of visibility samples with a minimum number of antennas. In principle, one can measure the visibility function with just two antennas by mechanically varying their spacing. But this is not practical for the present application, and would require too much observation time for the sequential measurements. Instead, Geostar uses a thinned (or "sparse") array to simultaneously measure all the required spacings from a fixed geometry. There are many kinds of sparse arrays, and the "Y" array of Figure 2 is one of the best in terms of efficient use of antennas and in terms of the simplicity of the structure - which lends itself well to a spaceborne deployment. As illustrated in Figure 2, the spacings between the various antenna pairs yields a uniform hexagonal grid of visibility samples. By radio astronomy convention, the spacings are called the "baselines," with the dimensions "u" and "v." The area covered by this sampling grid is the synthetic aperture of the system, which is comparable to a real aperture of the same outer dimensions (e.g. a dish antenna). The primary advantage to the sparse array is that it uses far less physical antenna aperture than the comparable real aperture.

The smallest spacing of the sample grid in Figure 2 determines the unambiguous field of view, which for GeoSTAR must be larger than the earth disk diameter of 17.5 degrees when viewed from GEO. This sets both the antenna spacing and the horn diameter at about 3.5 wavelengths, or 2.1 cm at 50 GHz, for example. The longest baseline determines the smallest spatial scale that can be resolved. To achieve a 50 km spatial resolution at 50 GHz, a baseline of about 4 meters is required. This corresponds to approximately 100 receiving elements per array arm, or a total of about 300 elements. This in turn results in about 30,000 unique baselines, 60,000 uv sampling points (given conjugate symmetry), and 60,000 independent pixels in the reconstructed brightness temperature image.

3. Prototype Hardware

A small scale prototype is being built to address the major technical challenges facing GeoSTAR. The challenges are centered around the issues of calibration and power consumption. Synthesis arrays are new and untested in atmospheric remote sensing applications, and the calibration poses many new problems, including those of stabilizing and/or characterizing the phase and amplitude response of the antenna patterns and of the receivers and correlators. System requirements need to be better understood - and related to real hardware. And power consumption per receiver and correlator must be demonstrably low - given the very large number of receivers and correlators. To these ends the prototype is being built with the same receiver technology, antenna design, calibration circuitry, and signal processing schemes as are envisioned for the spaceborne system. Only the number of antenna elements differ. Progress on this system has been rapid in recent months, so the following discussion will attempt to emphasize the most recent achievements at the time of writing.

The prototype consists of a small array of 24 elements operating with 4 channels between 50 and 54 GHz. Figure 3 shows a current mechanical drawing of the prototype,

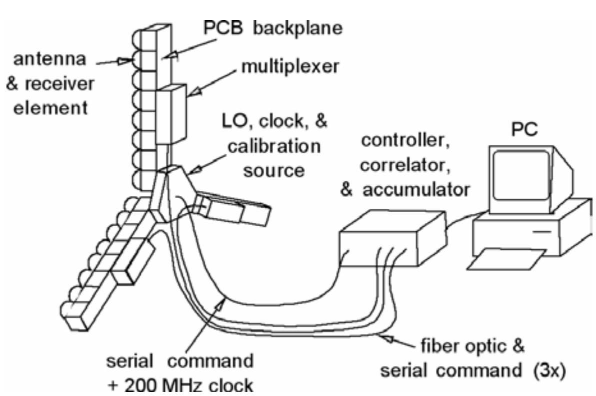

Fig 1. conceptual prototype configuration

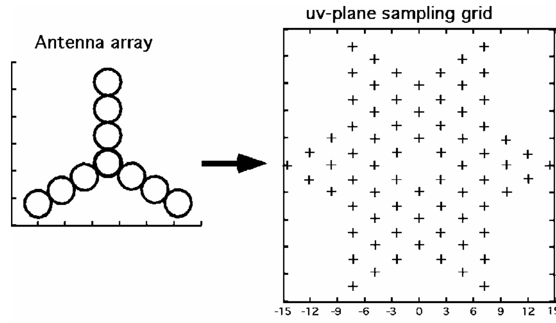

Fig. 2. Antenna array and UV samples

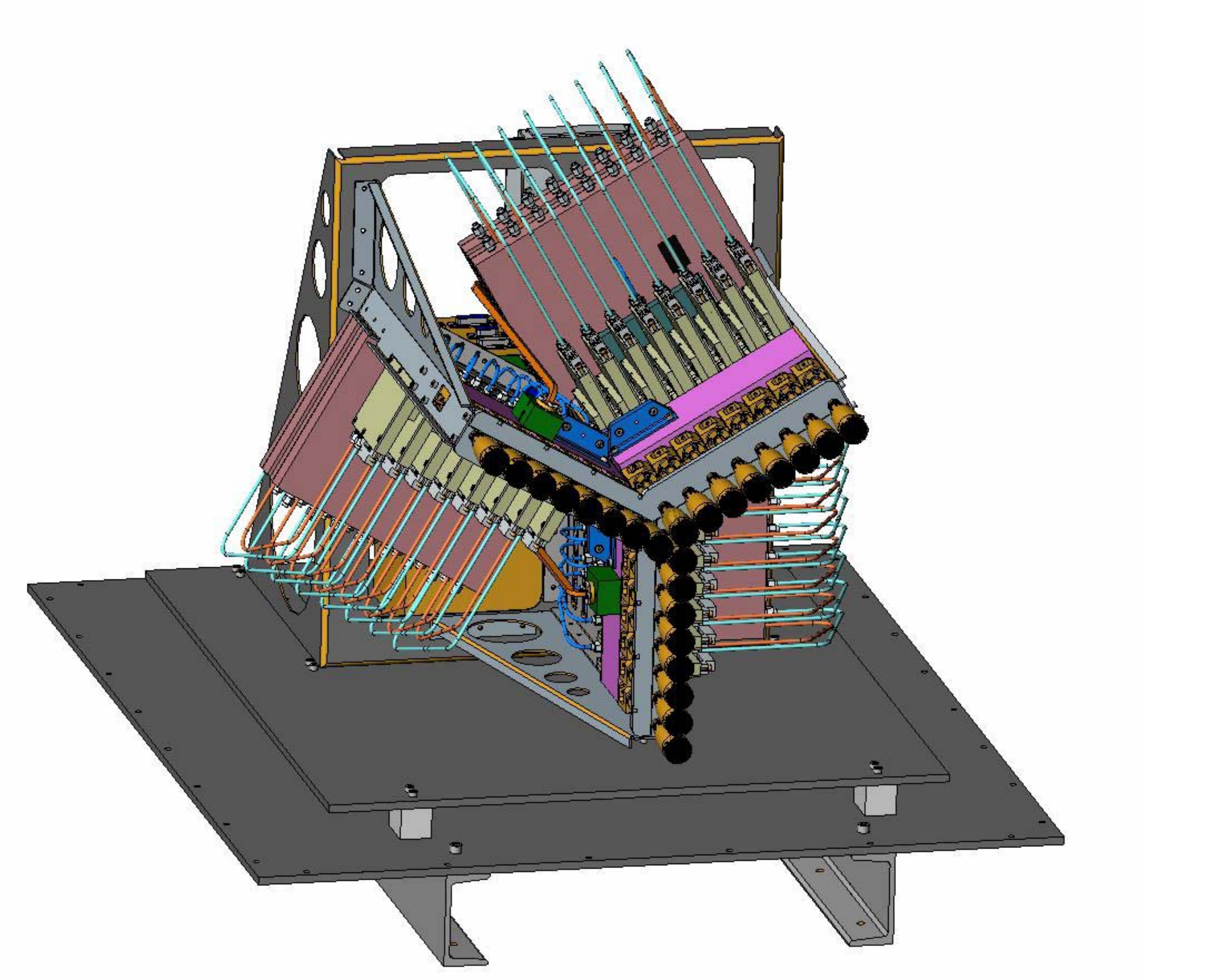

Fig. 3. recent drawing of the prototype

which has already evolved considerably from the earlier sketch of Figure 1. One change evident in Figure 3 concerns the basic layout of the Y array: note that (in contrast with Figure 2) there is no single horn at the center of the array. The center horn posed a number of unnecessary complications to the system, related to the physical package (there is not enough room) and the electrical design (to be discussed below). The solution in Figure 3 is to remove the one horn from the center of the array, stagger the three arms counter clockwise, and then bring them together so that the three inner most horns form an equilateral triangle. This staggered-Y configuration eliminates the need for an odd receiver at the center, which simplifies both mechanical and electronic design. The only penalty is a slight and negligible loss of visibility coverage.

A simplified block diagram of the GeoSTAR prototype is given in Figure 4. Figure 4 shows the signal flow from one of the 24 antennas through to the correlator. The major assemblies can also be seen in Figure 3. From left to right in Figure 4 - or from front to back in Figure 3 - the signal starts at the horn aperture with a vertical polarization, and then passes through a WR15 waveguide twist which aligns the waveguide to the orientation of the 8-element array arm. Each of the three arms require different twists: the top two arms of Figure 3 twist 60 degrees in opposite directions, and the bottom arm doesn't twist at all. An alternative polarization alignment scheme (which was originally proposed) would have used circular polarization to render the arm orientation irrelevant. This scheme was dropped due to costs and difficulties in obtaining a circular polarizer with a sufficiently well balanced polarization ratio. As discussed in the error budget below, GeoSTAR is very sensitive to antenna pattern differences among antennas, and a waveguide twist proved to be the easiest solution to guarantee a precise polarization match.

The signal in Figure 4 then passes through an 8-way calibration feed which periodically injects a noise diode signal into all receivers from a common noise diode source. This signal will be used as a reference to stabilize the system against gain, phase, and system noise drifts. The critical assumption here is that the calibration distribution network- which consists of power dividers and couplers- is more stable that the receiver RF, IF, and correlator electronics. This assumption will be carefully re-examined

quadrature by subharmonic mixers to two IF signals of 100 MHz bandwidth. The 100 MHz is defined by lumped

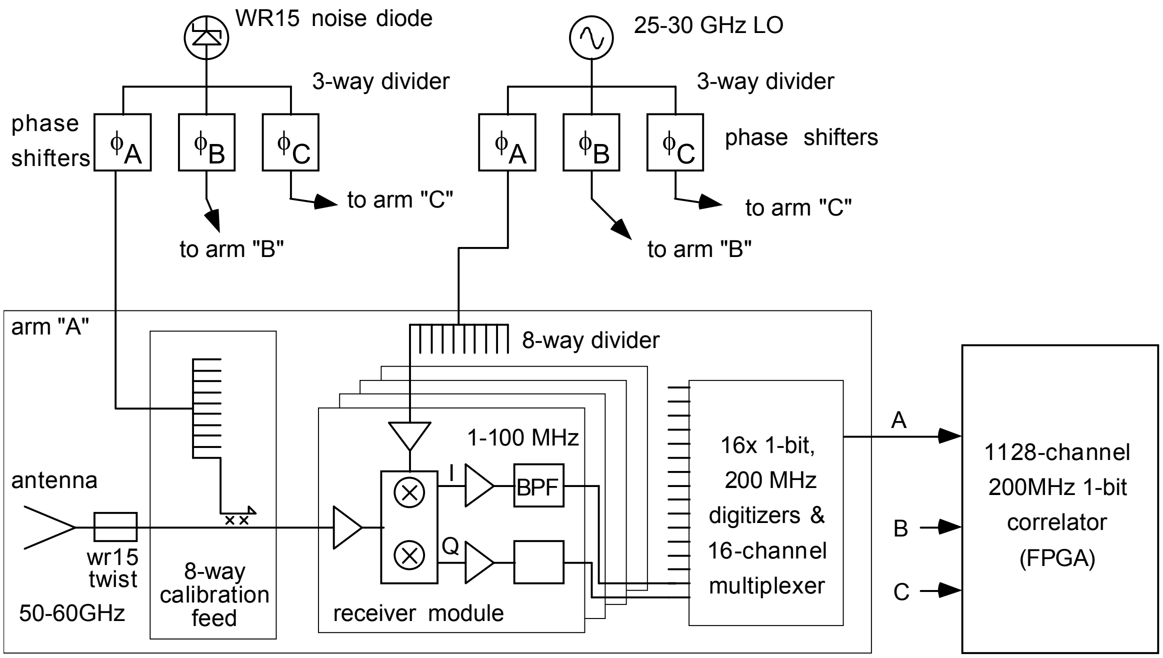

Fig. 4. Simplified block diagram

when the system is operational. The injected noise diode signal needs to be in the range of 1 to 10 Kelvin of equivalent noise temperature at the receiver input.

Note in Figure 4 that the noise diode will be distributed to the three arms via phase shifters. Each of these phase shifters consists of a pin diode and hybrid MMIC assembly which can switch between 0 degrees and 120 degrees. Correlations which occur between receivers of different arms can be exited by the noise diode with three possible phases using any two of these switches. This capability is critical to ensure that every correlator can be stabilized with respect to both phase and amplitude. Without this capability one must otherwise depend on perfect quadrature balance of the complex correlations- which is predictably not perfect. It is also worth noting that the phase of the noise diode can not be shifted among the 8 antennas of a given arm, but that such a capability is not needed given the staggered-Y arrangement of the antennas. With the staggered-Y all correlations within an arm represent visibility samples which are redundant to samples which can otherwise be obtained between elements of different arms. These redundant correlations are not needed for image reconstruction, so they do not need to be calibrated.

Continuing the discussion in Figure 4, the antenna signal passes into the MMIC receiver module where it is amplified (noise figure of 3dB) using InP FET low noise amplifiers, and then double-sideband downconverted in phase

element filters. A photograph of a pre-prototype receiver module is provided in Figure 5. The local oscillator operates from 25 to 30 GHz, and is distributed via three phase shifters. These MMIC phase shifters periodically shift the phase of each arm by 90 degrees (180 degrees at RF) to provide a means of switching the correlator phase and chopping out correlator biases. Again, the staggered-Y arrangement of the array proves crucial to this function since one would otherwise need phase shifters within each arm (this was indeed the original proposal- and it proved impractical due to the timing complexity when switching phase among all 24 receivers).

The in-phase and quadrature IF signals from each receiver are then digitized at a clock rate of 200 MHz. For reasons of product availability, the analog to digital converter is

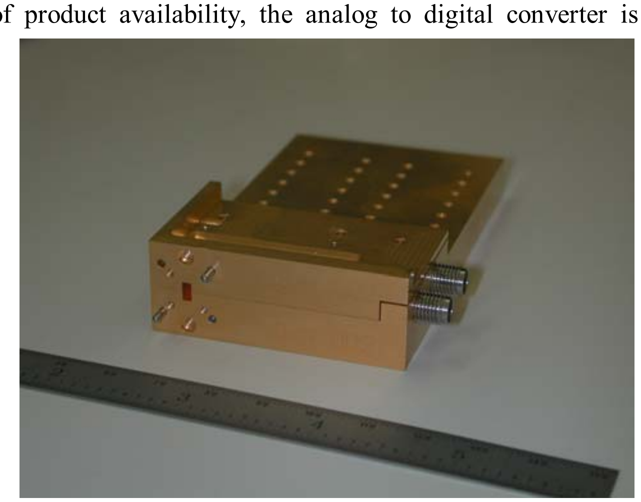

Fig. 5. Pre-prototype receiver module

presently an 8-bit device, but minimally this could be

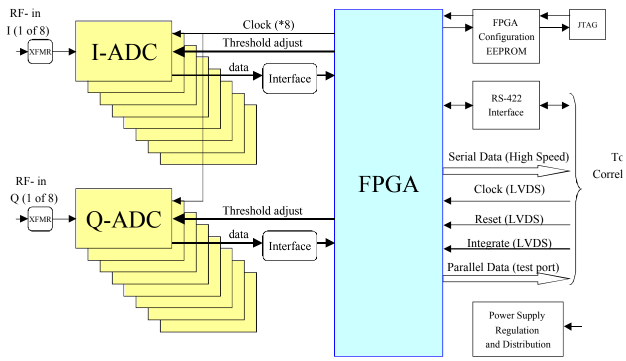

Fig 6. Signal multiplexer

replaced with a two-bit or possibly just a one-bit converter. The correlations only require 1-bit (i.e. the sign bit), and the extra bits are only used to monitor changes in system noise temperature. The ADC and multiplexer assembly is shown in greater detail Figure 6. There is a single multiplexer for each arm of the array, and the term "multiplexer" refers to the fact that eight receivers are combined on a single digital bus for transmission to the central correlator. The FPGA of the multiplexer also includes "totalizers" (not shown) which are used to count the occurrences of each ADC output state so that the threshold levels can be compared with the known Gaussian statistics of the IF voltage.

Perhaps the most important subsystem is the correlator, which must perform multiplications of all 100-MHz signal pairs in real time. The correlator for the GeoSTAR prototype is shown in Fig. 7, and its interfaces with the rest of the system are shown in Fig. 8. For an spaceborne operational system with 100 elements per arm, as discussed earlier, that requires on the order of 20 trillion multiplications per second. To achieve such a high processing rate with a reasonable power consumption, the correlators are implemented as 1-bit digital multiply-and-add circuits using a design developed for the University of Michigan. 1-bit correlators are commonly used in radio astronomy. The correlator for the GeoSTAR prototype, where low cost is more important than low power consumption, will be implemented in FPGAs. An operational system will use low-power application specific integrated circuits (ASICs).

4. SYSTEM STUDIES

In parallel with the hardware development, a number of system studies have been conducted to establish basic instrument hardware requirements. These studies have thus far depended on numerical simulations which model the earth brightness temperature as viewed from GEO, and then apply a number of presumed instrumental errors to examine their effects on reconstructed images. The primary errors of concern are (1) antenna pattern errors, (2)

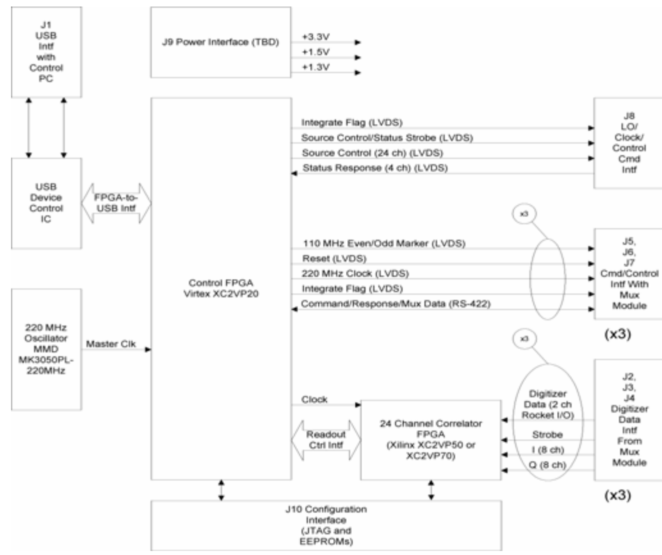

Fig 7. Correlator

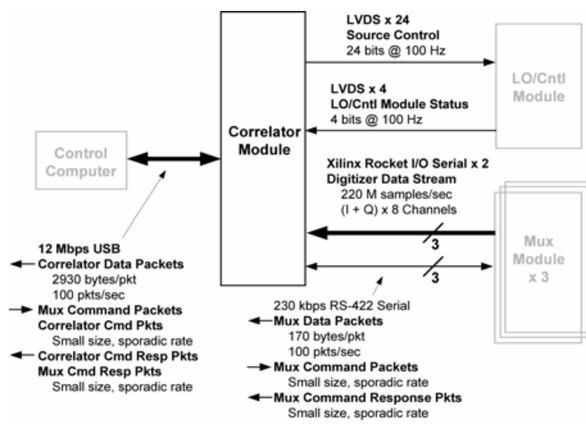

Fig 8. Correlator interfaces

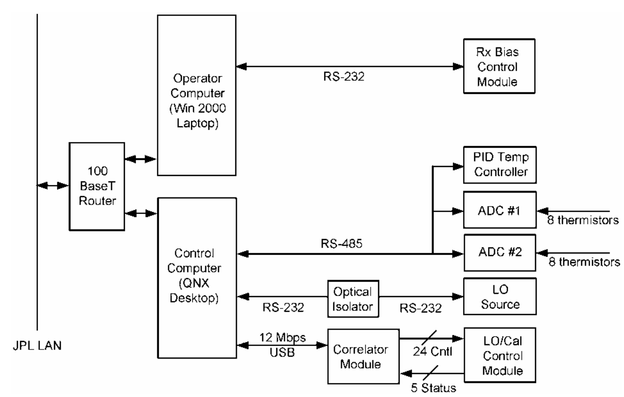

Fig 9. C&DH subsystem

additive correlator errors such as those caused by correlator null offsets, and (3) gain and phase errors, such as those caused by uncertainty in the system noise temperature (which is needed to scale the raw 1-bit correlations to visibility - in units of Kelvin). The overriding requirement is that the sum of all errors be no more than 1 K in brightness temperature.

The antenna pattern factors into the image reconstruction directly, and our studies have confirmed one simple fact, which is that image errors are proportional to antenna pattern uncertainty. A 0.1% uncertainty in the elemental antenna power pattern will cause 0.3 Kelvin of uncertainty given a 300 K brightness temperature, for example. This is a critical concern as it will require that the elemental antenna patterns very accurately characterized. This will be very difficult if there is any significant amount of scattering or mutual coupling among neighboring elements. Our initial prototype work carefully considered various antenna design options, and in the end we fabricated and tested the two most promising horn designs. One was a linear taper horn, and the other was a variant of a Potter horn which we call the Parabolic Potter horn. Both designs needed to maximize the antenna gain from 51 to 58 GHz within the 2.1 cm of available space. This is because the antenna brightness temperature is marginal from GEO. At best, about half of the energy spills over the edge of the earth. This spillover is a direct loss for the system which affects the signal to noise ratio. The high gain requirement lead to very shallow horn angles, and also ruled out corrugated horns. The two horn designs were tested on the antenna range with the specific goal of determining the significance of scattering and mutual coupling. This was done by comparing antenna range power while rapidly switching dummy horns in and out of a test jig, as shown in Figure 10. These tests revealed that the linear taper horns (which do not suppress the edge illumination in the E-plane) where much more sensitive to the proximity of neighboring elements at the 1 to 5% level. The Parabolic Potter horn was perturbed at the 0.1 to 0.3 percent level, which is acceptable.

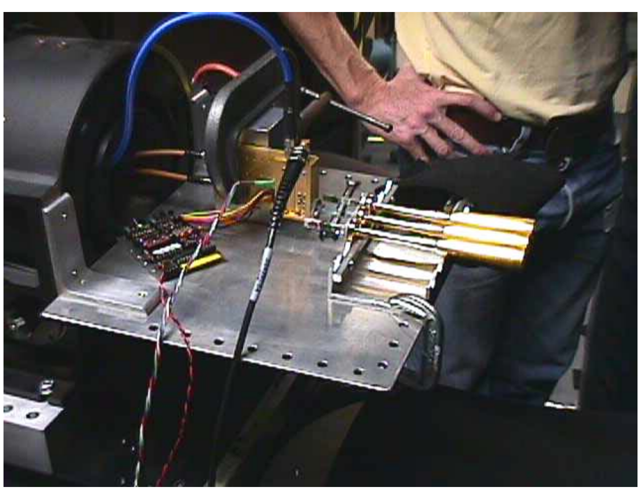

Fig. 10: Antenna range tests of horns

The second type of error examined in the numerical simulations were additive correlator errors. These include correlator null offsets and correlator “delta-T” noise due to the finite bandwidth and integration time. The latter is the inherent radiometer error which has been well appreciated from the start. GeoSTAR will produce a new image of the earth in approximate 15 minute time slices, and this time will be fully utilized as integration time to reduce this error to an acceptable level. The errors caused by null offsets are more worrisome, however, as no amount of integration time will necessarily defeat them. These errors also become more stringent as the array size increases. Our simulations show that biases must be well below 0.001 K for the full scale spaceborne system. This is a very low bias when compared to the system noise temperature of 500 K. Our system design has therefore incorporated a number of mechanisms to estimate and eliminate biases. The local oscillator phase shifters are a key feature in this regard- but we are as yet uncertain as to how well these circuits will perform since the local oscillator itself may distribute common mode noise into all receivers (which will cause a bias). We have examined this issue using the noise spectra of available sources and the measured mixer isolation of our prototype receivers. Under certain worst case scenarios we may not meet requirements. Anticipating this, we have recently increased the RF gain of the receivers prior to the mixer. We also plan is to operate the prototype local oscillator from a low noise laboratory synthesizer until these problems are understood.

Lastly, the third type of error is of gain and phase. These are multiplicative errors which scale with the magnitude of the visibility. GeoSTAR will view the earth from GEO, and the effects of gain and phase errors - our simulations have shown - are entirely dependent on the assumed brightness temperature model. The spatial spectra of the earth’s temperature and the contrasts within the FOV at the continental boundaries and limb all indicate that visibility magnitude decreases as a function of distance from the UV plane origin. This implies that the gain and phase requirements will be most stringent for closely spaced antennas, and relaxed for large spacings. This is convenient because the largest spacings will also be more difficult to align in phase, due to the mechanical tolerances of the array. Using some crude 1/f spectral models of the earth spatial temperature variability along with the actual antenna element pattern of our Parabolic Potter horn, we have determined that the spaceborne GeoSTAR will see about 10 K of visibility in only the smallest baselines, and typically less than 0.5 K in the majority of larger baselines. We have translated these results to the following requirements: Gain and phase uncertainty for small baselines should be less than 0.3% and 0.2 degrees, respectively. Phase uncertainty can then increase linearly to a maximum of 4 degrees at the largest baseline.

6. Conclusions

The GeoSTAR prototype construction is nearing completion. Our efforts are focused on building a practical low power system which will form the basis of future spaceborne proposals. We are very carefully examining error budgets, and hope to demonstrate a comprehensive and well justified system calibration based on real hardware.

Acknowledgments

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